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Shock Response of Boron Carbide

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Abstract

Boron carbide is of interest because of its potential application in protective systems both for personnel and structures. Therefore it is necessary to determine its mechanical response when subjected to impact loading. The present work was undertaken to determine tensile/spall strength of boron carbide under plane shock wave loading and to analyze all available shock compression data on boron carbide materials obtained from different sources. The principal conclusions are: (1) the tensile/spall strength of boron carbide when shocked between 2 and 15 GPa is 0.35 ± 0.07 GPa, (2) the existing shock compression data indicates that boron carbide tends to suffer a gradual loss of its shear strength as the magnitude of shock stress exceeds its Hugoniot Elastic Limit (HEL), i.e., 15–20 GPa, (3) the underlying reason or reasons for the inferred loss of shear strength under plane shock wave compression remains to be investigated, and (4) a general equation of state for boron carbide in its ambient phase is formulated which can adequately represent its hydrodynamic compression up to a strain of 0.25, i.e., to a maximum stress around 70 GPa.

Acknowledgments

Mr. P. K. Bartkowski performed spall experiments. Author is grateful to Dr. D. E. Grady for sharing his re-analyzed boron carbide data. Discussions with Drs. G. R. Johnson and T. J. Holmquist and J. M. Boteler were very helpful during the preparation of this report.

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1. Introduction

Boron carbide is a potentially attractive material for a lightweight armor system due to its low density in comparison with the other monolithic ceramics such as Al_2O_3, SiC, and TiB_2. Generally, the ability of ceramics to retain a high compressive strength and shear strength under compression make them attractive. However, the propensity of ceramics to fail under a small tensile stress due to their inherent low ductility presents a challenge to their use as a protective element of an armor system. To discover whether ceramics used in some combination with other materials can be used effectively in an armor system, it is important to determine their tensile strengths under impact loading condition. Shock Hugoniot of boron carbide has been investigated by Wilkins (1968), Gust and Royce (1971), McQueen et al. (1970), Pavlovskii (1971), and Marsh (1980). Later Kipp and Grady (1989) and Grady (1995) reported shock and release response of two different boron carbides manufactured by Eagle Pitcher and Dow Chemical, respectively. Recently, Grady (1999) re-analyzed the shock compression data on boron carbide manufactured by Eagle Pitcher and Dow Chemical. The reanalyzed data is incorporated in this report. The boron carbide material used in the investigation of McQueen et al. (1970) was porous with only 75–78% of the single crystal density, i.e., 2.52 Mg/m^3. The densities of boron carbide used in the remaining investigations varied between 2.31 and 2.52 Mg/m^3. Hence, the data from the investigation of McQueen et al. (1970) is not included in this work. Grady (1995) also performed a limited number of experiments to measure spall strength of boron carbide manufactured by Dow Chemical. Winkler and Stilp (1992) reported spall strength of hot-pressed boron carbide. The source of their material was not reported. Brar et al. (1992) determined the Hugoniot Elastic Limits (HEL) of boron carbides with densities varying between 2.13 and 2.52 Mg/m^3. The material used by Brar et al. (1992) was manufactured by Dow Chemical. The present work was undertaken to measure spall strength of a hot-pressed B_4C, marketed as PAD B_4C by CERCOM INC (hereafter referred to as B_4C throughout this report to distinguish it from other boron carbide materials) and to analyze the existing shock Hugoniot data on the nonporous boron carbides previously mentioned to determine the equation of state and to determine the nature of the inelastic deformation above its HEL.

At present, no independent equation of state measurements on boron carbide exist to compare with the derived equation of state presented in this work. However, the results presented in this report will enable modelers to simulate the ballistic data generated to test the impact worthiness of boron carbide. They also suggest important avenues for additional experiments on boron carbide for

uses in applications where the impact-induced stress exceeds 20 GPa or steady state pressures at the impactor-target interface exceed that pressure. For example, an impact stress of 20 GPa is attained in a tungsten impactor and a boron carbide target when the velocity of impact is 1 km/s.

2. Materials and Their Properties

CERCOM INC manufactured the boron carbide used in the present study. This material is currently used in ballistic investigations at the U. S. Army Research Laboratory (ARL). A general description of the procedure used to fabricate PAD B_4C provided by the manufacturer is as follows. CERCOM INC produces PAD B_4C by hot pressing, i.e., simultaneous application of heat and pressure, blended powders at approximately 2,273 K and 138 MPa pressure, under vacuum. The composition of the material is at least 99% boron carbide (boron 76.5% minimum and carbon 22.5% maximum), aluminum (1,500 ppm), silicon (2,000 ppm), iron (1,500 ppm), and titanium as the major metallic impurities. About 1/2% oxygen is usually present. The average grain size is 15 μm. The boron content is in the range of 76.5–77.1 weight-percent. The atomic ratio is slightly less than 4:1 as free boron results in the parts sticking to the graphite die used to fabricate the material. The values of measured density and ultrasonic longitudinal and shear wave velocities in nine specimens of this material are given in Table 1. The density was measured utilizing Archimedes' Principle. The ultrasonic wave velocities were measured following the method developed by Papadakis (1967). The longitudinal and shear wave velocities were measured at 10 and 5 MHz, respectively. The average values and associated errors (twice the respective standard deviation) of density, longitudinal, and shear wave velocities are 2.508 ± 0.016 Mg/m^3, 13.49 ± 0.18 km/s, and 8.65 ± 0.08 km/s, respectively. Boron carbide forms rhombohedral crystals and the lattice belongs to the R3m space group. The rhombohedral unit contains three molecules of B_4C (Wyckoff 1960). The single crystal density of boron carbide (B_4C) is 2.52 Mg/m^3 (Thevenot 1990). Thus, the average porosity of PAD B_4C material, in terms of pore volume fraction, is estimated to be 0.005.

The values of elastic constants calculated from the measured values of densities and ultrasonic wave velocities in PAD B_4C are given in Table 2. This table also provides properties of various boron carbide materials used in the earlier shock wave investigations. The values of the measured elastic wave velocities and derived elastic constants of boron carbide materials used by different investigators are similar except for the values of bulk moduli (263 GPa) and Poisson's ratios (0.241) reported by Wilkins (1968). Further, the values of sound

Table 1. Density and ultrasonic wave velocites for PAD B_4C.

Specimen	Density (Mg/m^3)	Wave velocities (km/s)	
1	2.512	13.507	8.633
2	2.489	13.424	8.581
3	2.513	13.519	8.642
4	2.511	13.541	8.658
5	2.513	13.679	8.715
6	2.508	13.481	8.710
7	2.498	13.352	8.647
8	2.512	13.456	8.629
9	2.513	13.436	8.642

Table 2. Description of the various boron carbides used in shock wave studies.

Items	Wilkins (1968)	Gust and Royce (1971)	Grady (1995)	Kipp and Grady (1989)	Winkler and Stilp (1992)	Brar et al. (1992)	Present work
Manufacturer		Norton	Dow Chemical	Eagle Picher		Dow Chemical	Cercom
Processing		Hot Pressed			Hot Pressed		Hot Pressed
Average grain size (μm)	30	—	3	10	—	1–3.5	15
Density (Mg/m^3)	2.50	2.503 ± 0.017	2.506	2.516	2.512 ± 0.005	2.13–2.52	2.508 ± 0.016
Void fraction	0.035	0.02	0.01	—	—	0.163–0.0	0.005
Wave velocities (km/s)							
Longitudinal (C_L)	13.90	13.78	14.07	14.04	14.07	11.85–13.42	13.49 ± 0.18
Shear (C_S)	8.12	8.53	8.87	8.90	8.81	7.47–8.46	8.65 ± 0.08
Bulk (C_B)	10.26	9.63	9.65	9.57	9.72	8.12–9.20	9.06 ± 0.22
Elastic Moduli (GPa)							
Young's (E)	410	432	461	463	453	278–422	432 ± 11
Shear (G)	165	182	197	199	195	119–180	188 ± 4
Bulk (K)	263	232	233	230	237	140–213	206 ± 11
Poisson's Ratio (ν)	0.241	0.188	0.17	0.164	0.177	0.17–0.18	0.151 ± 0.014
HEL (GPa)	15.0	15.0	17–19	14.0–14.8	16.7	9.6–19.4	16.0[c]
Yield strength (Y)[a] (GPa)	10.2	11.5	10.7–15.1	11.3–11.9	13.1	7.6–15.4	13.2[c]
Shear strength[b] (GPa)	6.8	7.7	9.0–10.1	7.5–7.9	8.7	5.1–10.1	8.8[c]
Lateral stress[b] (GPa)	4.8	3.5	3.5–3.9	2.7–2.9	3.6	2.0–4.2	2.8[c]
Spall Strength (GPa)			0.4–0.5		0.59–0.77		Stress dependent

[a] Yield strength (Y) is calculated assuming Von Mises yield criterion, i.e., $Y = \{(1-2\nu)/(1-\nu)\}$ HEL.
[b] Shear strength equals (2/3) Y. Lateral stress equals $\{\nu/(1-\nu)\}$ HEL.
[c] HEL is assumed to be 16 GPa. It remains to be determined for PAD B_4C. The values of Y and shear strength correspond to the assumed value of the HEL.

wave velocities, and consequently, the values of elastic moduli for nearly fully dense boron carbide manufactured by Dow Chemical reported by Brar et al. (1992) are consistently smaller than the values of respective elastic parameters by Grady (1995). Lacking information about the technique used to measure the elastic wave velocities and the errors associated with these measurements, the reported systematic difference in the values of elastic properties of nearly fully dense boron carbide materials is hard to understand and explain. The previous statement is made under an implicit assumption that the compositions of boron carbide manufactured by Dow Chemical used in their investigations were identical. Only Gust and Royce (1971) provide detail information about the elemental composition and boron to carbon ratio of their material. The composition of their material (in weight percentage) was Si (0.08), Ca (0.1), Mg (0.02), Ni (0.01–0.05), Al_2O_3 (0.1–0.5), and the remainder was boron and carbon. The boron to carbon ratio in their material was 3.93:1.

Table 2 also includes the calculated magnitudes of yield strength, shear strength, and the lateral stress developed in boron carbide materials at the plane shock wave induced stress equal to their respective HEL values. The magnitude of shear strength is the difference between the value of the HEL and hydrodynamic pressure required to attain the strain at the HEL. The magnitude of lateral stress is the stress under inertial confinement that a material is subjected to during the plane wave shock experiments under uniaxial strain condition. Fowles (1961) and Jones and Graham (1971) discuss these relationships in detail.

Table 3 gives the measured values of densities, longitudinal wave velocities (C_L), and Poisson's ratios (ν) for boron carbides (Brar et al. 1992). The magnitudes of Young's, bulk, and shear moduli, and shear and bulk wave velocities given in this table are calculated from the measured quantities. It should be noted that the values of shear wave velocities given by Brar et al. (1992) are not consistent with the corresponding values of longitudinal wave velocities and Poisson's ratios.

Table 3. Densities and measured elastic properties of boron carbides (Brar et al. 1992).

Sample	B_4C85	B_4C90	B_4C95	B_4C98	B_4C100
Density (Mg/m^3)	2.13	2.25	2.33	2.43	2.52
Wave velocities (km/s)					
Longitudinal	11.85	12.52	12.80	13.02	13.42
Shear	7.60	8.22	8.47	8.73	8.90
Bulk (calculated)	7.96	8.16	8.26	8.24	8.63
Poissons ratio					
Brar et al.	0.17	0.18	0.18	0.18	0.17
Present work	0.151	0.121	0.110	0.092	0.107

3. Shock Experiments

Shock experiments were performed to measure spall strength of B_4C as a function of impact-induced stress on an ARL light gas gun facility. Two experiments were performed to examine the effect of shock compression duration on the spall strength of this material. The general configuration of these experiments is shown in Figure 1. In a symmetric shock experiment, a thinner disc of B_4C (impactor) impacted another B_4C disc in the target with a given velocity to generate a shock compression wave of a certain magnitude. In a nonsymmetric experiment, a thinner disc of tungsten carbide (WC) impacted a B_4C disc in the target with a given velocity to generate a shock compression wave of a certain magnitude. The wave velocity profiles in these experiments were monitored at the free surface of the target by means of a velocity interferometer technique (VISAR) developed by Barker and Hollenbach (1972). The impact velocities were measured by shorting four electrically charged pins located at measured distances a few millimeters ahead of the target disc. The details of this type of experiment may be found in the published literature of Bartkowski and Dandekar (1996). The planarity of impact was better than 0.5 mrad. The precision of free surface velocity measurements is 1%. The uncertainties in the measure values of impact velocities are 0.5%.

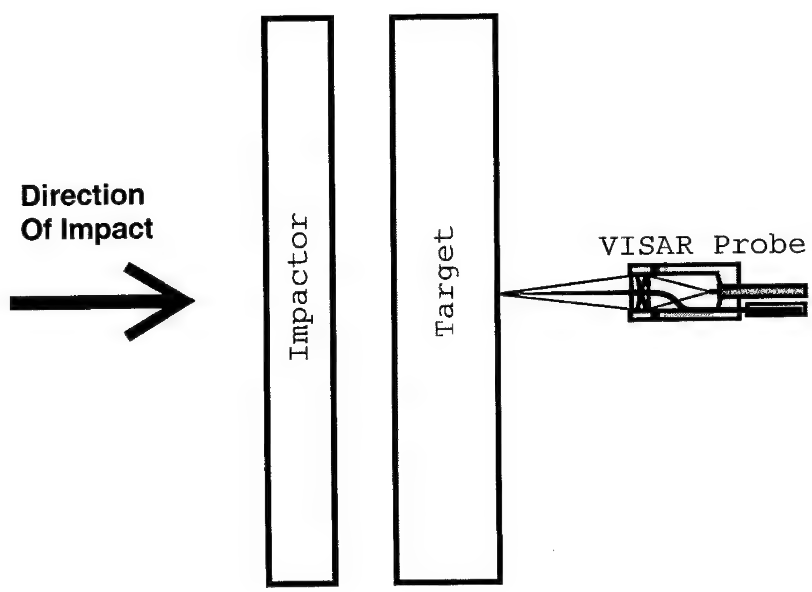

Figure 1. Configuration of spall experiments.

B_4C specimens used in the shock wave experiments were 40 ± 1 mm in diameter. The thicknesses of the B_4C targets, and B_4C or WC are given in Table 4. Specimens used in these experiments were lapped until they were flat and parallel within 10 μm. Precise thickness measurements were then taken to the nearest micron. Target specimens were then prepared to produce a diffuse reflective surface, for use with the laser and VISAR diagnostics. Using a diffuse reflective surface minimizes the chances of a data signal being lost due to slight misalignments that may occur during the shock wave experiments. Boron carbide specimens were hand polished using a diamond paste to produce the desired reflectivity.

Table 4. Experimental data for PAD B_4C.

Experiment	Thickness (mm)		Impact velocity (km/s)	Pulse width (μs)	Free surface velocity (km/s)		
	Impactor	Target			Shock	Spall	Reshock
825	4.052	5.956	0.6129	0.60	0.623	0.604	0.624
826	WC/2.033	5.957	0.6106	0.59	0.904	0.890	0.903
828	4.053	5.958	0.4086	0.60	0.411	0.389	0.411
829	4.051	5.956	0.2327	0.60	0.230	0.209	0.230
833–1	4.063	5.960	0.412	0.60	0.414	0.394	0.414
833–2	2.043	5.954	0.412	0.30	0.411	0.384	0.411
840	4.053	5.956	0.1228	0.60	0.120	0.101	0.120
846	WC/2.028	5.954	0.5070	0.59	0.772	0.752	0.772
910	2.043	4.058	0.1229	0.30	0.118	0.093	0.118

4. Results

4.1 Spall Experiments

Tables 4 and 5 summarize the results of spall experiments conducted on PAD B_4C. Table 4 gives the measured values of target and impactor thicknesses, impact velocity, pulse width (i.e., duration of the shock compression), and free surface velocities corresponding to impact-induced shock, tension, and reshock (i.e., recompression of the spalled material). In this table, whenever a WC impactor was used in an experiment, the thickness of the impactor follows its identification. The remaining experiments employed boron carbide as the impactor. A tungsten carbide impactor was used to induce higher stresses in boron carbide. Table 5 gives the values of shock-induced stress, mass velocity, density change, release impedance, and spall-related parameters, namely, half the pull-back velocity ($1/2\,\Delta u_{pb}$) and spall strength.

Table 5. Results of shock wave experiments in PAD B_4C.

Experiment	Impact velocity (km/s)	Shock			Release	Spall/Tensile strength	
		Stress (GPa)	Mass velocity (km/s)	Density (Gg/m^3)	Impedance (Gg/m^2s)	$1/2\ \Delta\ u_{pb}$ (km/s)	Stress (GPa)
825	0.6129	10.37	0.3065	2.566	32.8	0.0095 ± 0.004	0.32 ± 0.14
826	0.6106	15.54	0.4595	2.596	35.0	0.0070 ± 0.006	0.24 ± 0.20
828	0.4086	6.91	0.2043	2.547	33.4	0.0120 ± 0.003	0.41 ± 0.10
829	0.2327	3.94	0.1164	2.530	34.6	0.0105 ± 0.002	0.36 ± 0.07
833–1	0.4120	6.97	0.2060	2.547	36.3	0.0090 ± 0.003	0.30 ± 0.10
833–2[a]	0.4120	6.97	0.2060	2.547	35.7	0.0135 ± 0.003	0.46 ± 0.10
840	0.1228	2.08	0.0614	2.519	35.4	0.0095 ± 0.001	0.32 ± 0.03
846	0.5070	12.91	0.3815	2.581	33.0	0.0100 ± 0.005	0.34 ± 0.17
910[a]	0.1229	2.08	0.0615	2.519	36.8	0.0125 ± 0.001	0.42 ± 0.03

[a] Pulse widths in these experiments were 0.3 μs. The pulse widths in the other experiments were 0.6 μs.

The free surface velocity profiles recorded in experiments with a shock-induced compression duration of 0.6 μs are shown in Figure 2. The profiles of these experiments are arbitrarily shifted in time to preserve the clarity of the figure. Thus relative time duration of each profile represents a chronology of events occurring due to propagation of shock waves. These profiles show a shock-induced jump in the free surface velocity of a given magnitude persisting for about 0.6 μs followed by a sudden small decline in the free surface velocity (identified as spall signal in Figure 2) and finally attaining a velocity nearly identical in magnitude to the first jump in the free surface velocity. The column $1/2\ \Delta\ u_{pb}$ in Table 5 is half the magnitude of difference in the free surface velocities under shock and spall given in Table 4. The errors associated with various entities in Table 5 are as follows: impact stress (1.6%), mass velocity (0.5%), density (1.5%), and release impedance (4.5%). The errors in the values of $1/2\ \Delta\ u_{pb}$ range between 0.001 km/s and 0.006 km/s corresponding to free surface velocities 0.120 km/s in experiment 840 and 0.904 km/s in experiment 826, respectively. Thus the values of spall threshold stress are subject to larger uncertainties.

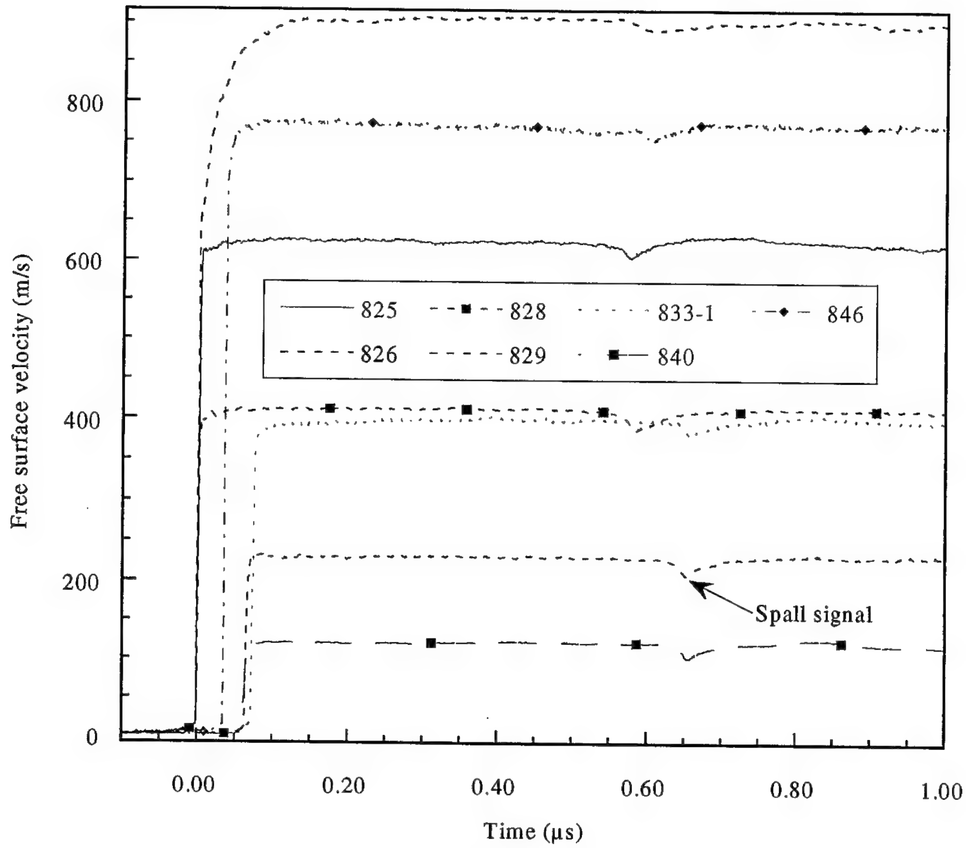

Figure 2. Free surface velocity profiles recorded in B_4C.

The HEL of near fully dense boron carbide has been reported to range between 15 and 19 GPa (Table 2). The maximum impact stress generated in the present work is 15.5 GPa. The wave profiles shown in Figure 2 indicate that the material used in this work remains elastic to this maximum stress. The values of release impedance vary between 33 and 37 Gg/m^{2}s and compares favorably with the ultrasonic longitudinal impedance 33.8 ± 0.5 Gg/m^{2}s. This inference is further strengthened by the agreement between the measured values of free surface velocities due to shock and reshock following the spallation of boron carbide (Table 4 and Figure 2).

Table 5 shows that spall strength as measured directly by $1/2\ \Delta\ u_{pb}$ declines with an increase in the impact stress. Its value of 0.012 km/s at the lowest shock-induced stress of 2.1 GPa declines gradually to 0.007 km/s at a shock-induced stress of 15.5 GPa for a pulse width of 0.6 μs. Two experiments (833–2, and 910) were done to examine the effect of pulse width on spall strength of boron carbide. These were done at shock stresses of 7.0 and 2.1 GPa, respectively. Thus if generation and propagation of defects were time dependent these would show up at low magnitudes of shock stresses rather than high values of shock stresses.

It should be noted that two experiments in 833 were conducted simultaneously to avoid any possibility of difference in the recorded profiles being attributed to inexact replication of the impact condition. Figures 3 and 4 show the free surface velocity profiles from these experiments. These profiles clearly show the effect of pulse widths on the magnitudes of spall related change in the value of the free surface velocities. However, a consideration of the errors incurred in the calculation of $1/2\ \Delta\ u_{pb}$ suggests that these differences are probably insignificant. Thus one may conclude that the spall strength of boron carbide is not pulse width dependent in the absence of other experimental evidence to the contrary. Finally, the values of spall strength in terms of stress calculated from the product of elastic impedance and $1/2\ \Delta\ u_{pb}$ are given in Table 5.

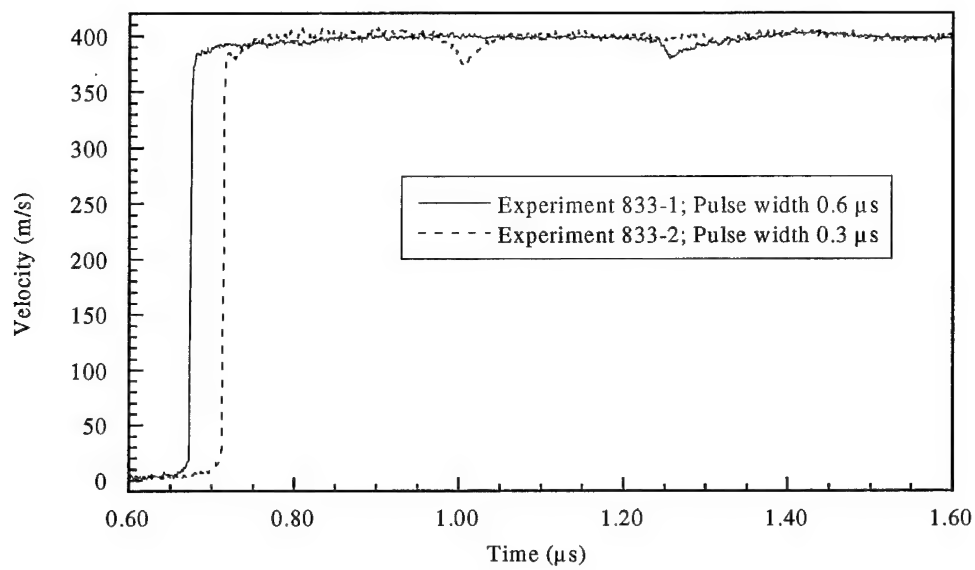

Figure 3. Effect of pulse width on spall threshold of B_4C.

Winkler and Stilp (1992) and Grady (1995) have measured the spall strengths of boron carbides. The source of the material used in the investigation of Winkler and Stilp is unknown. Dow Chemical produced boron carbide was used in the investigation of Grady. But both materials were produced by a hot pressed technique. Grady reported spall strength of boron carbide to be 0.45 GPa when shocked to 3 and 7 GPa. Spall strengths of boron carbide from the investigations of Winkler and Stilp (1992) are shown in Figure 5. This figure shows that the values of spall threshold reported by Winkler and Stilp are consistently higher than those found in the present work and reported by Grady (1995). This is the case even when one takes into account errors associated with the values of $1/2\ \Delta u_{pb}$. For example, the value of the spall strength of PAD B_4C used in the present work at 2 GPa is at the most equal to 0.42 ± 0.03 GPa whereas its value is

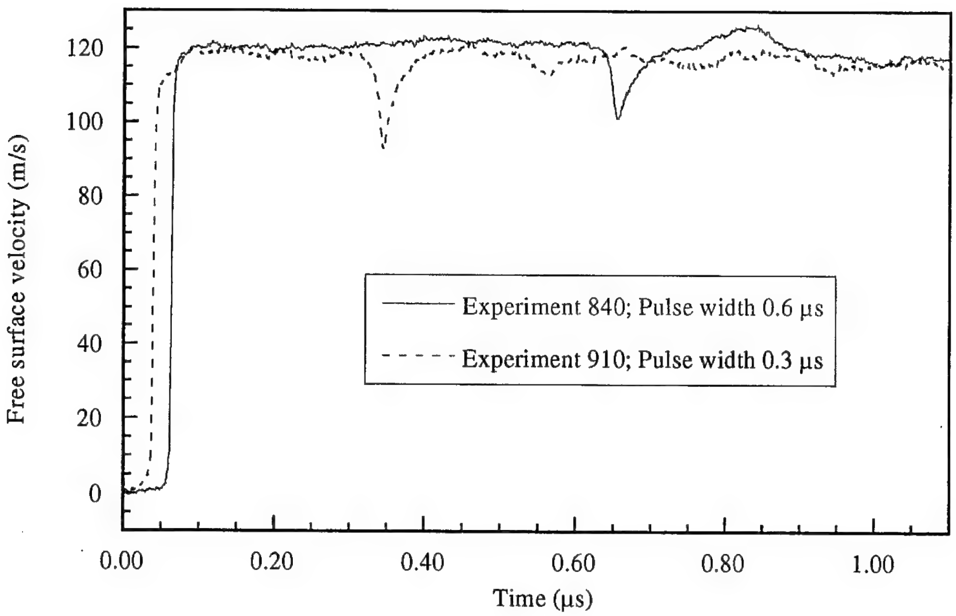

Figure 4. Effect of pulse width on spall threshold in B_4C.

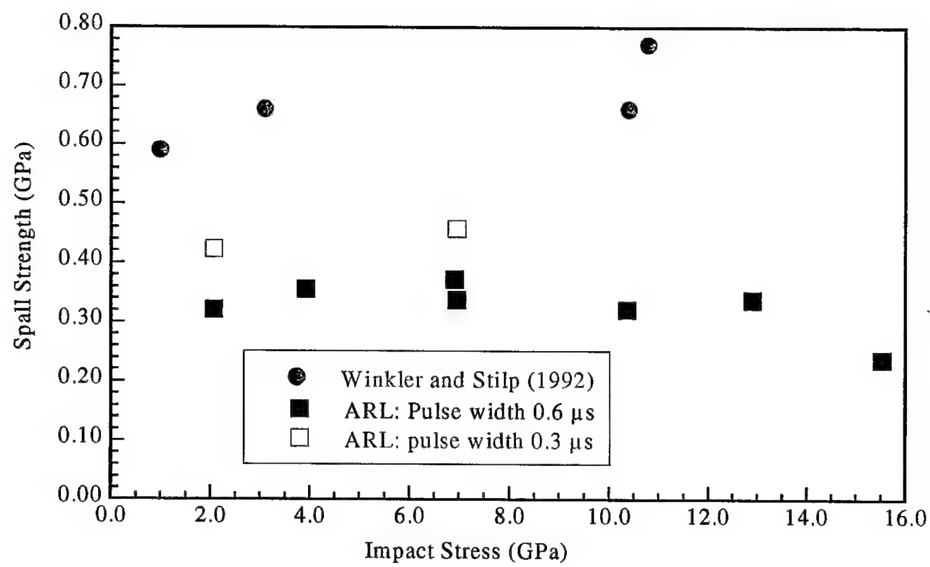

Figure 5. Spall strength of boron carbide vs. impact stress.

0.59 in their work at similar shock stress. Thus, the differences in the values of spall thresholds of these two boron carbides may be real. However, the observed increase in the values of spall threshold (Figure 5), reported by Winkler and Stilp (1992), with an increase in the shock stress is real only if the precision of free surface velocity measurements is better than 1%. The values of the spall threshold obtained by Grady (1995) are not significantly different from those of this work.

4.2. Shock Hugoniot and Hydrodynamic Compression

It is well known that the shock Hugoniot for nontransforming material with a low compressibility is adequately represented by a linear relationship between its shock velocity (U_s) and particle velocity (u_p). The slope (s) of this linear relationship is used in the calculations of the hydrodynamic compression of the material and the pressure derivative of its bulk modulus. The generated hydrodynamic compression of a material used in conjunction with its shock Hugoniot data permits a first order estimate of magnitude of shear strength sustained by the material under plane shock wave loading. This estimate represents a maximum limit of the shear strength a material can sustain under inertial confinement. Since, the shock velocity-particle velocity data reported by Marsh (1980) were presumed to be hydrodynamic in nature, it is examined first. However, the initial densities of boron carbide specimens used in the investigation varied between 2.312 to 2.452 Mg/m^3. This presents a problem related to applicability of the magnitude of slope (s) obtained from their data for use in generating hydrodynamic compression for near fully dense boron carbide investigated by Wilkins (1968), Gust and Royce (1971), and Grady (1999). In the present work, the following procedure is adopted to solve the above-mentioned problem. Two linear relations between U_s–u_p are computed using the least squares technique. The first linear relation is obtained using all the applicable shock velocity-particle velocity data. The second relation is obtained using shock velocity-particle velocity data corresponding to initial densities of boron carbide varying between 2.407 Mg/m^3 and 2.452 Mg/m^3. If these two relations do not differ significantly from one another, then the variability in the initial densities (i.e., porosities of boron carbide) does not affect the slope and, thereby, the magnitude of the pressure derivative of the adiabatic bulk modulus. This is a very unlikely case. If these two relations differ significantly, then the slope (s) of the second relation is more likely to be representative of the near fully dense boron carbide material.

Figure 6 shows a plot of pressure (P) versus volume ratio (V/V_0) (i.e., ratio of initial density [$\rho(0)$] and density [$\rho(P)$] at pressure (P) for boron carbide). The initial densities varied between 2.31–2.39 Mg/m^3 and 2.41–2.45 Mg/m^3. This figure shows that Pressure-volume ratio coordinates of boron carbide with densities in the above two ranges do not appear to lie on a single locus. Further, this figure shows a cusp around 15 GPa due to the elastic precursor. In other words, the Hugoniot data reported by Marsh (1980) is not totally hydrodynamic in nature. Hence, the hydrodynamic compression of boron carbide must be generated from a linear relationship between shock and particle velocities measured at and above the pressure when a single shock wave carries the material in its final compressed state. This pressure is determined by the intersection of the elastic Rayleigh line extending from zero pressure with the

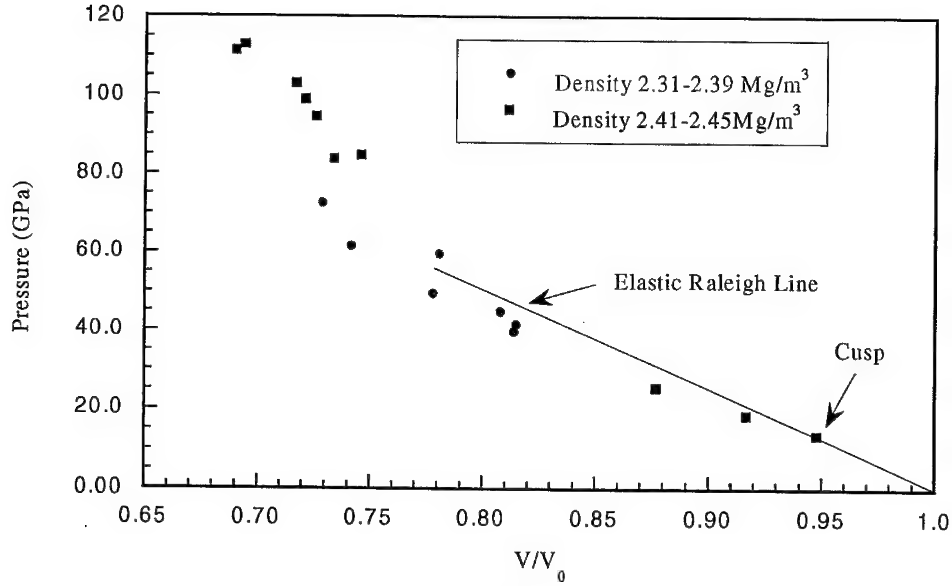

Figure 6. Compression of boron carbide (Marsh 1980).

Hugoniot coordinate as indicated in this figure. This pressure is estimated to be 60 GPa. This leaves only two Pressure-volume ratio coordinates of boron carbide with initial densities lower than 2.40 Mg/m^3 for inclusion in the calculation of the first relation. The two linear relations obtained from the all the applicable data from Marsh (1980) and from the data pertaining to higher initial densities of boron carbide are, respectively,

$$U_s = 6.15 + 1.690\ u_p,\ r=0.89 \tag{1}$$

and

$$U_s = 8.88 + 0.914\ u_p,\ r=0.89. \tag{2}$$

In the above relations, r is the value of the correlation coefficient. The investigation by Brar et al. (1992) shows that the bulk sound wave velocity of boron carbide in the density range of 2.13–2.52 Mg/m^3 varies between 8.12 km/s and 9.20 km/s (Table 3). Therefore, the initial value of the shock velocity, i.e., 6.15 km/s in relation (1) is unrealistic for boron carbide with a density in the range of 2.31–2.45 Mg/m^3. However, the initial value of shock velocity in the equation (2) is consistent with the estimated value of bulk sound wave velocity (9.02 ± 0.08 km/s) of boron carbide with average density of 2.43 ± 0.03 Mg/m^3. It should be pointed out that the relation (2) was based on seven pairs of shock and particle velocity measurements above 60 GPa. A large scatter in the data yielded a low value of correlation coefficient (i.e., 0.89). This leads to large uncertainties in the least squares estimates of the initial shock velocity and the slope(s). The errors associated with the estimates of the initial shock velocity and the slopes are ± 0.71 km/s and ± 0.210, respectively.

In what follows, the value of the slope(s), i.e., 0.914 is used in the relation (2) to calculate the hydrodynamic compression of boron carbide because this relation was obtained by using the measured values of shock and particle velocities reported by Marsh (1980). Hydrodynamic compression of such a material is calculated from equation (3),

$$P = \rho(0)C_0^2.\eta/(1-s\eta)^2, \tag{3}$$

where P is pressure, C_0 is the initial shock velocity, η is the $[1-\rho(0)/\rho(P)]$, and $\rho(0)$ and $\rho(P)$ are densities at zero pressure and pressure (P), respectively.

The value of U_s at zero particle velocity in the least squares relation (2), i.e., C_0 is used to estimate the bulk modulus (K_0) of boron carbide used in the investigation of Marsh (1980). The value of K_0 is 192 GPa for boron carbide with an average density of 2.43 Mg/m^3. The shock Hugoniot data of Marsh (1980) and the calculated hydrodynamic compression curve of boron carbide using the above relation are shown in Figure 7. It shows that the calculated compression curve reasonably reproduces the experimental data for boron carbide with initial densities between 2.40 and 2.45 over the entire pressure range. The relation between the value of s and first pressure derivative of the initial adiabatic bulk modulus (K') is given by equation (4),

$$K' = 4s-1. \tag{4}$$

Equation (4) was derived by Ruoff (1967). Thus, the value of K' for boron carbide obtained from the data of Marsh (1980) is 2.66.

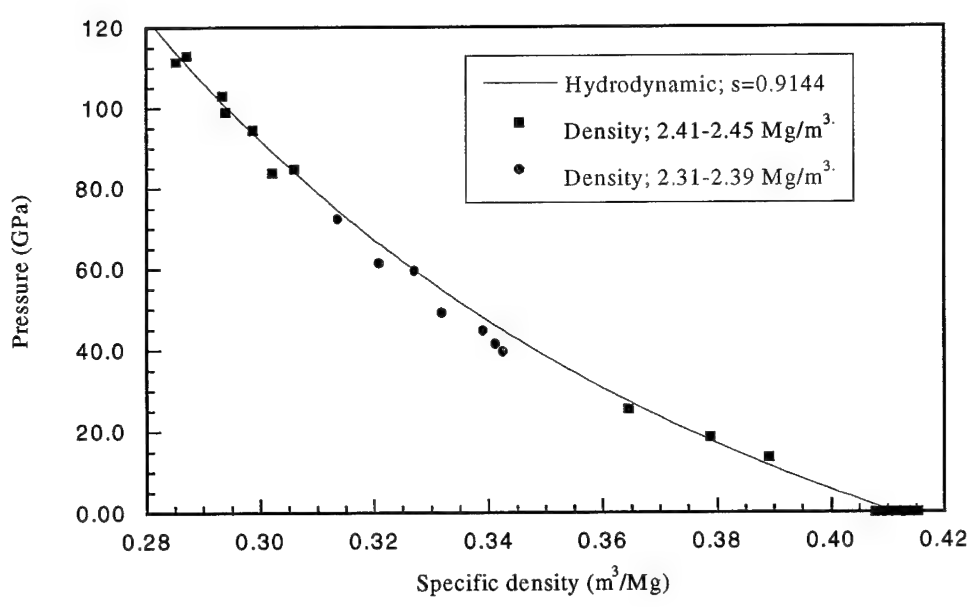

Figure 7. Hydrodynamic compression of boron carbide (Marsh 1980).

Hydrodynamic compressions for boron carbides used in the investigations of Wilkins (1968), Gust and Royce (1971), and Grady (1999) use the values of respective bulk moduli given in Table 2 and the value of s obtained in the relation (2). This procedure is considered to be appropriate because in none of these investigations the final shocked state was attained by overdriving the respective elastic precursors. Thus the final shock-induced states in their investigations were calculated with reference to their respective HELs.

Figure 8 shows the calculated hydrodynamic compression for the boron carbide materials investigated by Wilkins (1968). The value of K_0 used for the computation of the hydrodynamic compression is 263 GPa (Table 2). Figure 8 shows that the offset between Hugoniot stress and hydrodynamic pressure at the same value of V/V_0 tends to decrease above the HEL (15 GPa). The shear stress offset becomes zero around 40 GPa. This implies that the material is undergoing a gradual loss of its shear strength when the stress exceeds the HEL, and the loss is total when stress exceeds 40 GPa. This inference about the possible loss of shear strength is further strengthened by observing that the values of shock velocities slightly above the HEL of 15 GPa ranges from 9.58 km/s to 9.78 km/s compared to initial bulk sound velocity of 10.26 km/s measured in the ambient condition (Table 6). Graham and Brooks (1971) showed that one of the characteristics of materials showing a loss of shear strength under plane shock wave propagation is that the shock velocity values are less than local bulk sound speed. The shock data of Wilkins show this characteristic.

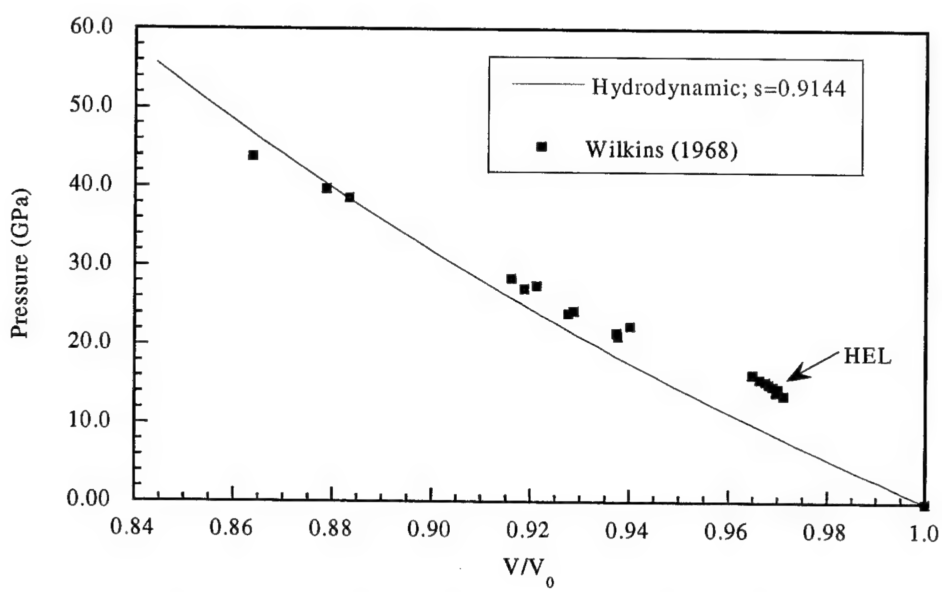

Figure 8. Compression of boron carbide (Wilkins 1968).

Table 6. Values of shock velocity in boron carbides just above the HELs.

Wilkins (1968)		Gust and Royce (1971)		Grady (1999)	
Stress (GPa)	Shock Velocity[a] (km/s)	Stress (GPa)	Shock Velocity (km/s)	Stress (GPa)[b]	Shock Velocity[b] (km/s)
21.1	9.58	20.4	8.03	23.8/24.6	8.13/9.04
21.5	9.75	21.2	9.40	29.0/31.2	8.48/9.95
22.4	10.39	20.4	9.20	40.2/40.5	9.10/9.20
24.0	9.57	26.6	9.34	25.8/26.5	8.68/9.33
24.3	9.78	27.0	9.14	55.9/56.0	10.18/10.22
27.1	9.93	29.4	10.77		
27.5	10.33	28.4	9.79		
28.4	10.09	26.8	9.79		
38.6	11.51	26.2	9.51		
39.7	11.44	23.1	9.16		
43.8	11.34	23.7	9.62		
		26.1	10.26		
		28.6	9.19		
		37.0	10.05		
		37.6	10.02		
		42.5	11.07		
		41.3	10.25		
		59.3	11.34		
		78.4	12.14		
		91.7	12.4		
		87.0	12.27		

[a] Shock velocities were calculated from the stress and densities given in Holmquist et al. (1999).
[b] The set of numbers preceding the slash sign are obtained using Transmitted technique and those following the slash are obtained by using Pulse-echo technique.

Figure 9 shows the calculated hydrodynamic compression for the boron carbide materials investigated by Gust and Royce (1971). This figure shows the boron carbide material used by Gust and Royce does not appear to suffer a total loss of its shear strength like the material used in the earlier investigation by Wilkins (1968). However, the values of shock velocity just above the HEL vary between 8.03 km/s and 9.19 km/s, less than the value of the initial local bulk sound velocity 9.63 ± 0.43 km/s (Table 6). To understand this contradictory behavior of boron carbide used in the investigation of Gust and Royce (1971), Figure 9 includes the bounds of hydrodynamic compression of their material (shown by the dashed loci) generated from the precision of the bulk modulus 232 ± 21 GPa (Table 2). It shows that from the experimental data of Gust and Royce (1971), the material must be undergoing some loss of shear strength, but the loss is not total.

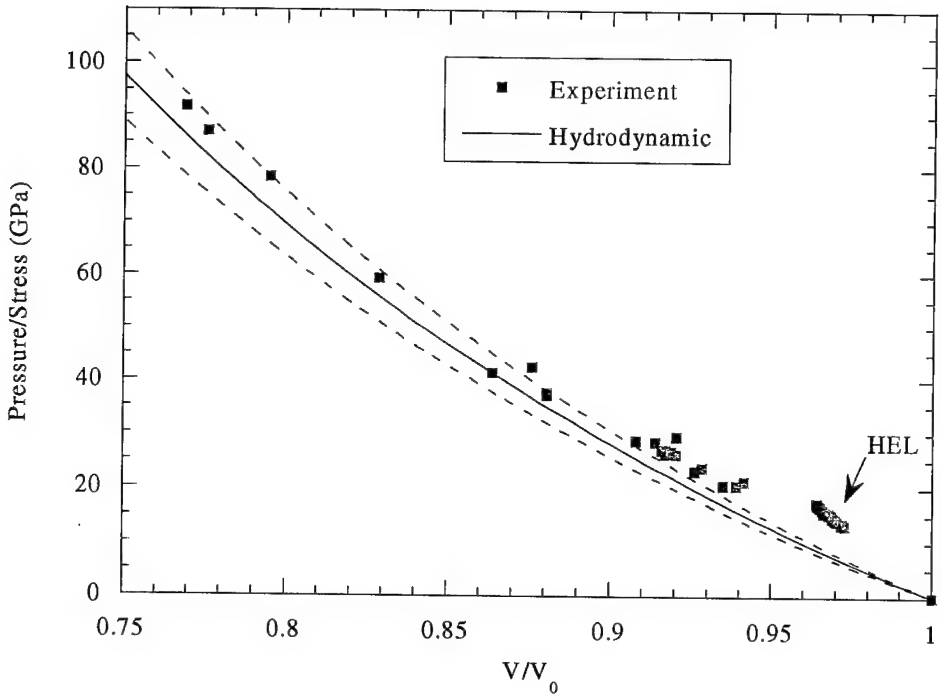

Figure 9. Compression of boron carbide (Gust and Royce 1971).

Gust and Royce come to a similar conclusion for boron carbide from their own analysis. However, following the suggestion of Graham and Brooks (1971), if their four highest stress (assumed to be least affected by the value of the HEL) and corresponding volume data are extrapolated, the value of η at zero stress is 0.0025. The value of shear stress offset (i.e., shear strength) calculated from the product of bulk modulus and η is 0.58 ± 0.05 GPa compared to its magnitude of 7.7 GPa at the HEL (Table 2). This suggests a loss of shear strength undergone by boron carbide at elevated stresses independent of errors associated with the hydrodynamic compression of boron carbide shown in Figure 9.

Finally, a plot of shock Hugoniot data of boron carbides with an initial density of 2.506 Mg/m^3 and 2.517 Mg/m^3 manufactured by Dow Chemical and Eagle Pitcher used in the investigation of Grady (1999) is shown in Figure 10. The coordinates for Eagle Pitcher and Dow Chemical materials are shown with hollow and solid symbols, respectively. Grady (1999) recalculated the Hugoniot states above the HEL attained in Dow Chemical material in his experiments by calculating the shock wave velocity in two ways. In the first case, the shock velocity was calculated from the signature of the release wave reflected from oncoming shock compression at the specimen-window interface. The estimate of shock wave obtained in this manner is called Pulse-echo estimate. The second method adopted to estimate the shock velocity is the traditional manner normally used in shock investigations and is referred to as transmitted estimate.

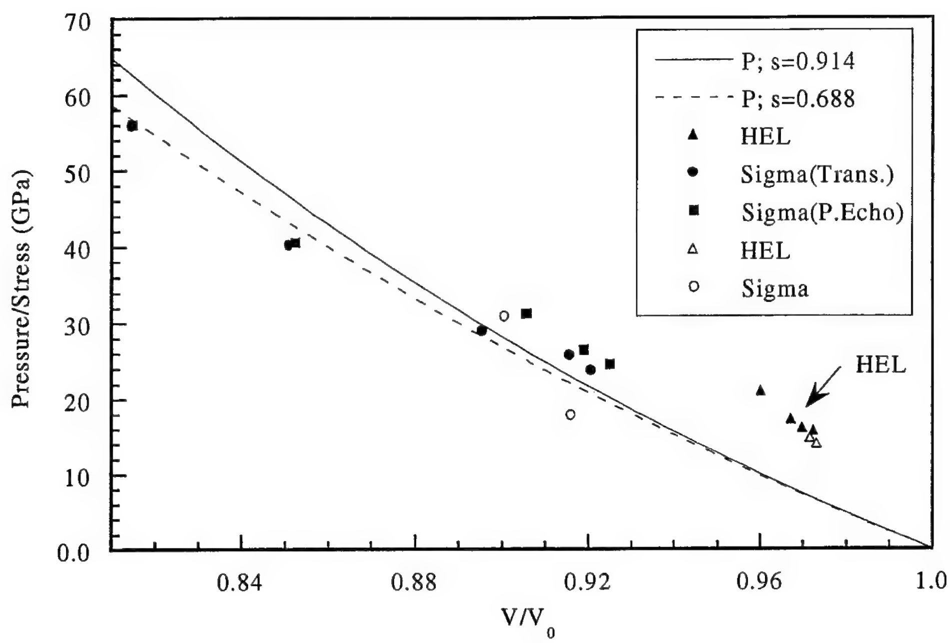

Figure 10. Compression of boron carbide (Grady 1999).

The differences in the Hugoniot states attained in boron carbide when shock velocities are calculated by these two techniques are insignificant (Figure 10). The Hugoniot data generated by Grady suggests Dow Chemical material undergoes a total loss of shear strength when shocked beyond 30 GPa. Eagle Pitcher material appears to undergo similar loss of shear strength. This is further supported by the fact that the magnitudes of shock velocities tend to be less than the initial bulk sound wave velocity 9.65 km/s for Dow Chemical material (Table 6). Grady (1995) came to a similar conclusion about the catastrophic loss of shear strength in boron carbide.*

The Hugoniot coordinates corresponding to 40 GPa and 59 GPa for Dow Chemical material are 5–6 GPa below the hydrodynamic compression curve of boron carbide. Considering the 1% error in VISAR measurements, this difference in the Hugoniot stress and hydrodynamic pressure is intriguingly too large. Further, to make these two Hugoniot points lie on a hydrodynamic compression curve, the value of s has to lie between 0.635 and 0.863. Pavlovskii (1971) measured shock velocity and particle velocity on a boron carbide material with a density of 2.51 Mg/m^3 in the pressure range 26–220 GPa. His lowest data at

* Recent measurements of elastic wave velocities in a fully dense boron carbide at high pressures by Manghnani et al. (2000) yield a value of the slope (s) to be 1.315. This implies that the hydrodynamic compression of boron carbide calculated from the results of Manghnani et al. (2000) will be stiffer than the ones calculated in section 4.2 and thereby reinforcing the inferred loss of shear strength in boron carbides at high pressures.

26 GPa seemed to be influenced by the propagation of the elastic precursor. The values of initial shock velocity and s calculated from the linear relation between the remaining three shock wave velocity and particle velocity measurements are 10.63 km/s and 0.688. The value of the initial bulk modulus of this material calculated from the initial shock velocity and density is 283 GPa. In order to understand the implication of the difference in the values of s obtained from the investigations of Marsh (1980) and Pavlovskii (1971), the values of pressures corresponding to the magnitudes of compression of boron carbide in the experiments of Pavlovskii (1971) were calculated assuming the value of s = 0.914 and values of bulk moduli 232 and 283 GPa, respectively. The results of these calculations are given in Table 7. These results show that the pressures obtained from his experiments and those calculated are reasonably close to one another except at 220 GPa. The calculated pressures required to attain a density of 4.22 Mg/m^3 in boron carbide in solid state are 237–289 GPa not the observed 220 GPa. This leads one to wonder whether such a density in boron carbide may be attained through the melting of boron carbide. Thus the data generated by Pavlovskii (1971) on boron carbide was partly in solid state and partly in liquid state. The reasonableness of this idea may be discerned from the calculated values of shock-induced temperature associated with these pressures and volume changes in solid boron carbide (Table 8). Temperature along the Hugoniot (T_H) at a given compression ($\xi = V_0/V$) is calculated from the following relation (Carter 1973):

$$T_H = T_0 \exp.[\gamma_0(\xi-1)/\xi^2]$$

$$+(s\, K_0/\rho_0 C_V) \exp.[\gamma_0(\xi-1)/\xi^2] \int \{[s-\xi\,(s-1)]^{-3} (\xi-1)^2 \exp.[-\gamma_0(\xi-1)/\xi^2]\, d\xi\}, \quad (5)$$

where γ_0 is the ambient Gruneisen gamma, C_V is the specific heat at constant volume, and the remaining symbols have already been identified earlier in the report.

Table 7. Shock Hugoniot data on boron carbide.

Data from experiments (Pavlovskii 1971)					Calculated pressures (GPa) s = 0.914	
Shock velocity (km/s)	Particle velocity (km/s)	Pressure (GPa)	Density (Mg/m^3)	Volume ratio	K_0 = 232 GPa	K_0 = 283 GPa
11.39	0.91	26.0	2.72	0.9228	21	25
11.50	1.25	36.1	2.82	0.8901	32	38
12.28	2.43	75.0	3.13	0.8019	68	84
14.73	5.96	220.0	4.22	0.5948	237	289

Table 8. Calculated values of shock-induced temperature on the solid Hugoniot of boron carbide.

	s = 0.914	s = 0.688
Volume ratio	K_0 = 232 GPa	K_0 = 283 GPa
0.9228	345	343
0.8901	396	387
0.8019	804	761
0.5948	8853	6124

These calculations were done assuming the ratio of Gruneisen Gamma (γ) and volume is constant. The values of Gruneisen Gamma (γ_0) and specific heat at constant volume for boron carbide at the ambient condition are 1.282 and 0.9616 J/gm/K. The calculated temperatures on the Hugoniot due to volumetric compression of 0.595 in boron carbide in solid state with s = 0.688 and K_0 = 283 GPa and s = 0.914 and K_0 = 232 GPa are 6124 K and 8853 K, respectively. The melting temperature of boron carbide at the ambient pressure is 2703 K. Thus the requirement of around 237–289 GPa to obtain a density of 4.22 in solid boron carbide and attainment of temperature in the range of 6124–8853 K strengthens the suggestion that the boron carbide Hugoniot determined by Pavlovskii (1971) could easily traverse solid and liquid states. The author is not aware of any experimental data pertaining to the change in melting temperature of boron carbide with pressure to substantiate the above suggestion. It is further complicated by the well-known fact in the shock literature that solid to liquid transition cannot be solely detected from the shock velocity and particle velocity data (McQueen et al. 1970).

In view of the above and a similarity in the deformation locus of boron carbide and that found in AlN that undergoes a phase transition around 20 GPa (Dandekar et al. 1994) there is a need to conduct careful shock experiments on boron carbide at comparable stresses to investigate whether the indicated loss of shear strength is mechanical in nature or due to a phase transition. The results of such an investigation will have an important impact on the use of boron carbide in an armor system. Briefly, all the currently existing shock Hugoniot data on boron carbides, irrespective of their sources, indicate that boron carbide suffers a partial or a total loss of its shear strength when shocked to and beyond 30–40 GPa. Consistent with the suggested loss of boron carbide and possible melting of it accompanied with a small volume change at the highest compression data, almost all the shock Hugoniot data on boron carbide with initial density equal to and greater than 2.50 Mg/m^3 very nearly lie on a single locus (Figure 11).

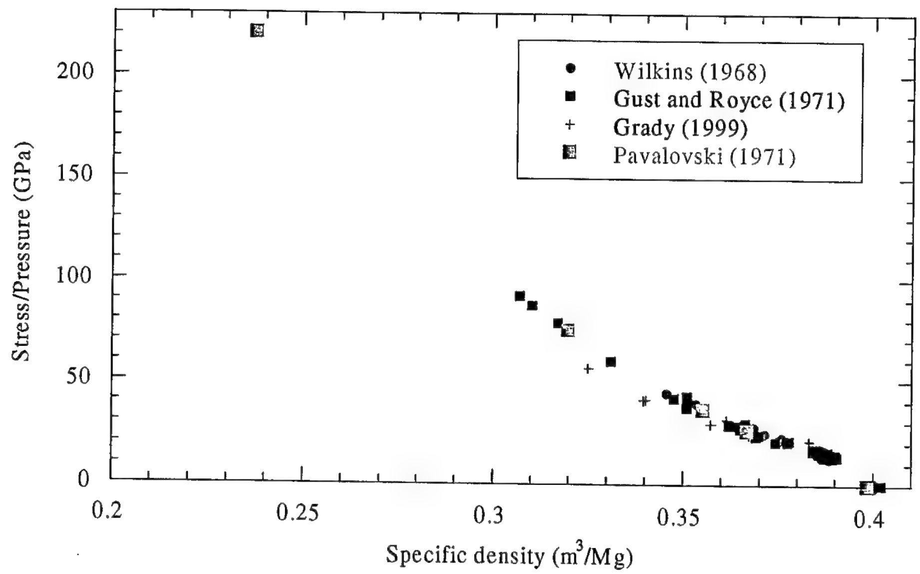

Figure 11. Shock compression of near fully dense boron carbides.

5. Discussion

Based on the results presented in the previous section, hydrodynamic compression of boron carbides investigated so far can be adequately represented by a relation (3) with a common s = 0.914, i.e.,

$$P = K_0.\eta/(1-0.914\eta)^2, \tag{6}$$

where the appropriate value of K_0 is substituted for a given material to calculate its relative change in change in volume (η) with pressure (P).

It is sometimes convenient to express pressures (P) as a polynomial function of (η) for numerical simulation of a ballistic event. Numerical simulation is done with the hydrodynamic compression of a material expressed as a third degree polynomial in η. In that case, the relation (3) may be rewritten as

$$P= K_0.\eta.(1-s\eta)^{-2}. \tag{7}$$

The term $(1-s\eta)^{-2}$ can then be expanded in powers of η as long as the value $(s\eta)^2$ is less than unity. The approximate relation becomes

$$P \cong K_0.\eta\ \{1+2s\eta+3\ (s\eta)^2\} = K_0.\eta + 2\ K_0s.\eta^2 + 3\ K_0s^2.\eta^3. \tag{8}$$

The three coefficients in relation (8) are identified as K_1, K_2, and K_3, respectively, in the numerical simulation literature (i.e., $K_1 = K_0$; $K_2 = 2\ K_0\, s$; and $K_3 = 3\ K_0\, s^2$). The values of these coefficients are in units of GPa. The values of the three

coefficients for the materials used in the previous shock experiments are set out in Table 9. These coefficients are all positive except the value of K2 in the work of Johnson and Holmquist (1999). Further, Johnson and Holmquist determined a value of K_3 that is 4 to 4.5 times larger than the other three values found for K_3. The reason for the observed discrepancies in the values of K_2 and K_3 is due to the fact that JH2 material model applied to simulate penetration requires a material to have non-vanishing shear strength, and so the constants K_2 and K_3 are determined through an iterative procedure which will simulate reasonably well the shock wave profiles and match the ballistic experiment data. In brief, their coefficients other than K_1 do not reflect observed loss of shear strength of boron carbide when shocked above 30–40 GPa as described in the last section. Hence, the compression of boron carbide based on their coefficients is not consistent with experimental evidence for a loss of shear strength in boron carbide presented in the last section, but it is only an artifact of the JH2 model. Since, Johnson and Holmquist (1999) chose the shock wave profiles in boron carbide obtained by Grady to calibrate their penetration model, it is of interest to plot Hugoniot data from Grady (1999) and hydrodynamic compressions of boron carbide obtained from equation (6), and equation (8) using the coefficients from the present work and those given by Johnson and Holmquist (1999). Such a plot is shown in Figure 12.

Table 9. Values of K_1, K_2, and K_3 for boron carbides used in the various shock studies.

	K_1	K_2	K_3
Wilkins (1968)	263	480	659
Gust and Royce (1971)	232	424	581
Grady (1999)	233	426	584
Johnson and Holmquist (1999)	233	−593	2800

The effect of truncation to the third degree of η is insignificant to 70 GPa. For example, when η is 0.25, the pressure calculated from the third degree polynomial is underestimated by 5%. However, the use of coefficients based on the model of Johnson and Holmquist leads to a much larger error in the value of pressure. Moreover, estimated pressures require that boron carbide retain shear strength contrary to the inference that it has no shear strength left above 30 GPa. Thus, the hydrodynamic compression of boron carbide based on the coefficients determined by Johnson and Holmquist could lead to erroneous results if used in conjunction with some other model for simulations of ballistic events.

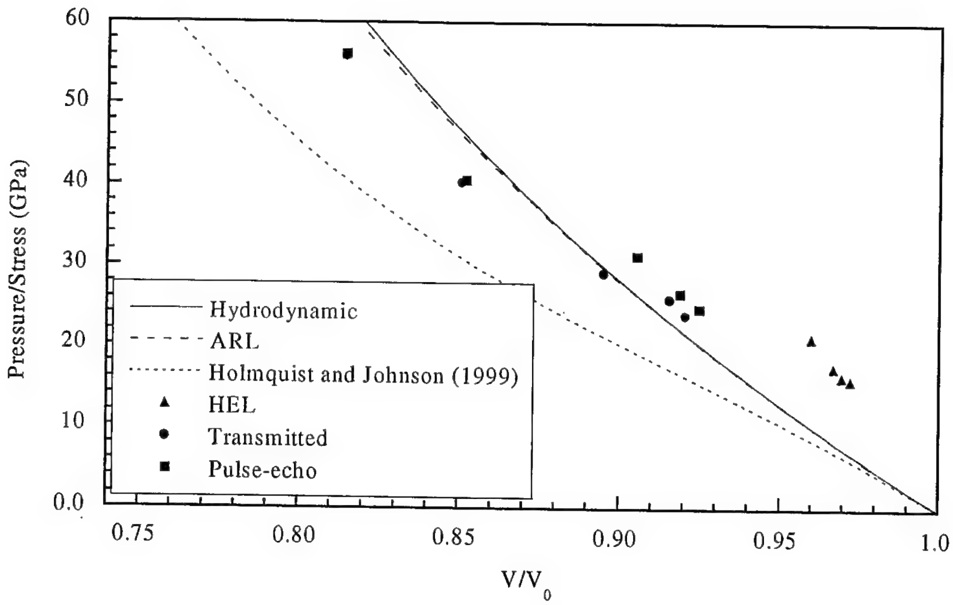

Figure 12. Comparison of compression curves for boron carbide (Grady 1999).

6. Summary

The results of the present investigation may be summarized as follows:

(1) The spall strength of PAD B_4C appears to be compressive-pulse-width dependent when shocked to 2 GPa. The values of spall strength for the pulse widths of 0.3 and 0.6 µs are 0.42 ± 0.03 GPa and 0.32 ± 0.03 GPa, respectively.

(2) The pulse-width dependence of the spall strength is not manifest when the impact stress is 7 GPa. The values of spall strengths for pulse widths of 0.3 µs and 0.6 µs are 0.30 ± 0.10 GPa and 0.46 ± 0.10 GPa, respectively. The values of spall strengths do not seem to vary significantly when initially stressed between 7 GPa and 15 GPa.

(3) Irrespective of the source of near fully dense boron carbide, the shock Hugoniot of boron carbides indicate some loss of shear strength when shocked beyond their respective HELs.

(4) The underlying reason or reasons for the inferred loss of the shear strength in boron carbide remains to be investigated.

(5) The difference in the values of slope(s) obtained from the investigations of Marsh (1980) and Pavlovskii (1971) raises the possibility that, whereas the

compression of boron carbide in the investigation of Marsh was attained in its solid state, the compression in the investigation of Pavlovskii was attained through solid and melt states of the material.

(6) The equation of state obtained from the hydrodynamic compression of boron carbide differ significantly from the equation of state used by Johnson and Holmquist (1999). The difference in the representation of the hydrodynamic compression arises from the fact that the material model proposed by these authors to simulate accurately the ballistic data require a material to retain shear strength under shock compression. This is contrary to the response of boron carbide under plane shock wave compression when the compressive stress exceeds 30 GPa.

7. Future Work

Since the stresses where the loss of strength in boron carbide is inferred can be easily reached at ordinance velocities, it will be necessary to confirm inferred loss of shear strength in boron carbide under shock induced compression independently. This can be achieved by conducting appropriate shock wave experiments above the HEL and by an independent determination of the equation of state of boron carbide. It will be most useful to generate shock data on PAD B_4C at stresses larger than those presented in this report to determine its HEL and the nature of its inelastic deformation beyond the HEL. It is equally important to determine the mechanism responsible for the loss of shear strength of boron carbide under shock loading. One of the possible mechanism may be due to its inability to deform plastically above its HEL like single crystal sapphire (Graham and Brooks 1971). Recently, Mashimo and Uchino (1997) reported that boron carbide exhibited a jagged wave profile at the free surface irrespective of whether its deformation was totally elastic or elastic-inelastic. The jaggedness of the observed wave profiles was attributed to heterogeneous shock front motion (i.e., heterogeneous deformation of boron carbide). Based on the observed spatial extent of the jaggedness in their profiles, they suggested that the macroscopic heterogeneous deformation behavior displayed by the boron carbide was not likely to be due to a dislocation process but may be due to propagation of cracks, cleavages, and melting zones. A second possibility is that boron carbide may be undergoing a phase transition where its Hugoniot points lie below the hydrodynamic compression curve like the case of aluminum nitride (Dandekar et al. 1994). At present, there exists no data that permits inference about the actual physical state of a nontransforming solid when it suffers a total loss of shear strength under plane shock wave compression. This leaves the physical meaning of the inferred loss of shear strength unanswered.

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Boron carbide is of interest because of its potential application in protective systems both for personnel and structures. Therefore it is necessary to determine its mechanical response when subjected to impact loading. The present work was undertaken to determine tensile/spall strength of boron carbide under plane shock wave loading and to analyze all available shock compression data on boron carbide materials obtained from different sources. The principal conclusions are: (1) the tensile/spall strength of boron carbide when shocked between 2 and 15 GPa is 0.35 ± 0.07 GPa, (2) the existing shock compression data indicates that boron carbide tends to suffer a gradual loss of its shear strength as the magnitude of shock stress exceeds its Hugoniot Elastic Limit (HEL), i.e., 15-20 GPa, (3) the underlying reason or reasons for the inferred loss of shear strength under plane shock wave compression remains to be investigated, and (4) a general equation of state for boron carbide in its ambient phase is formulated which can adequately represent its hydrodynamic compression up to a strain of 0.25, i.e., to a maximum stress around 70 GPa.

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